Prompt Neutrons and Fission Modes

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In our understanding of the nuclear fission process, what happens near the scission point where the two nascent fragments separate remains unclear. Observations of the final fission products in terms of charge, mass, and kinetic energy distributions provide indirect clues about the process. Another indirect but closer probe of the physics near scission is to look at the characteristics of the neutrons emitted by the fission fragments right after their separation. These so-called prompt neutrons are emitted from the excited primary fragments until they settle in a stable state of a nucleus (before eventually undergoing a subsequent beta-decay).

We have studied the consecutive emissions of prompt neutrons and gamma-rays by simulating the decay chain of the primary fission fragments. Each stage (i.e., each neutron emission) of this decaying sequence is treated exactly, assuming an evaporation process from a temperature-dependent Weisskopf spectrum. This type of simulation provides a large set of data, and can help reveal interesting correlations among the emitted neutrons (e.g., in energy, angle, multiplicity).

As an example, Monte Carlo simulations were performed for the low-energy neutron-induced fission of ^{235}U, for incident energies varying from 0.5 to 6.0 MeV. As an input to our simulations, the recently measured fission fragment yields *Y(A,TKE)* from Hambsch were used [1]. Here, *A* represents the mass of the fission fragment, and *TKE* is the total kinetic energy of the two complementary fragments. These yields were fitted using fission modes as defined in the Brosa model [2]. Roughly speaking, these fission modes originate from different paths leading to fission taken by the nuclear system along a multi-dimensional potential energy surface.

The experimental yields *Y(A,TKE)* at 0.5 MeV incident neutron energy are depicted in Fig.1, along with their decomposition in fission modes. As an example, the dominant S2 mode (~75% of the total) corresponds to an asymmetric fission (a light fragment and a heavy fragment are created) and to medium-to-high *TKE* values, corresponding to relatively compact shapes at scission. On the contrary, the SL mode corresponds to very elongated shapes with very low *TKE* values.

Monte Carlo simulations of the decay of the excited primary fragments were performed by sampling the *Y(A,TKE)* distribution for each fission mode. Figure 2 shows the average distributions of the neutron multiplicity $\langle\nu\rangle$ as a function of mass *A* and total kinetic energy *TKE*, for each fission mode. By projecting on the mass axis, we get the result shown in Fig. 3, and compared to available experimental data.

Only this level of detail in the calculations can help us better understand the physics near the scission point, and constrain theoretical models and physics assumptions. One particularly important question being addressed is: how is the total excitation energy available at scission shared between the two nascent fragments? In the particular situation shown here, the light fragment takes a larger share of this energy than its heavy counterpart, principally due to the difference in deformation energies of the fragments at scission.

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[1] F.J. Hambsch, IRMM Geel, Belgium, private communication (2007).
[2] U. Brosa, S. Grossmann, and A. Müller, *Phys. Rep.*, **197,** 167 (1990).
[3] P. Talou, to appear in *Conf. Proc. of the Int. Conf. on Nuclear Data for Science & Technology ND2007,* Nice, France, April 22-27 (2007).

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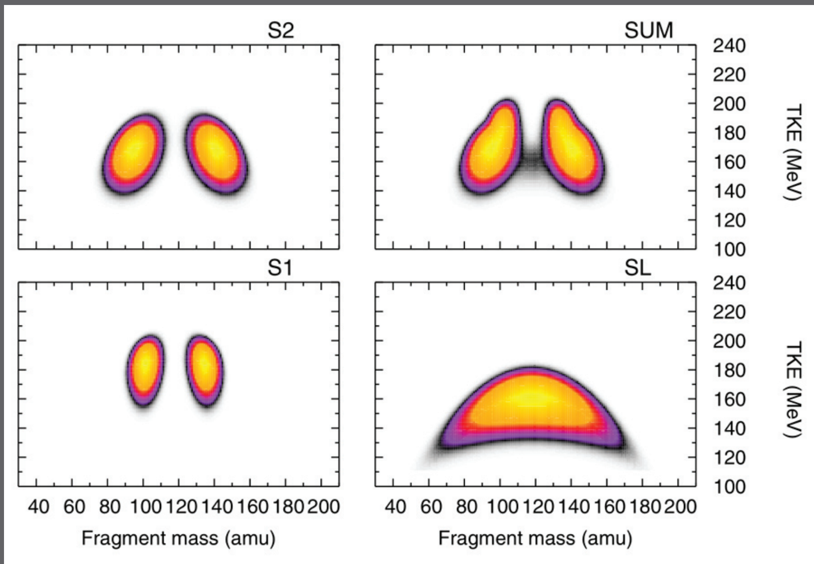

Fig. 1. Experimental yields Y(A,TKE) of n(0.5 MeV)+^{235}U and their decomposition in Brosa fission modes S1, S2, and SL. The top right plot labeled SUM corresponds to the full experimental distribution, i.e., the weighted sum of all three modes with the S2 mode representing about 75% of the total. TKE is the total kinetic energy of the two fragments.

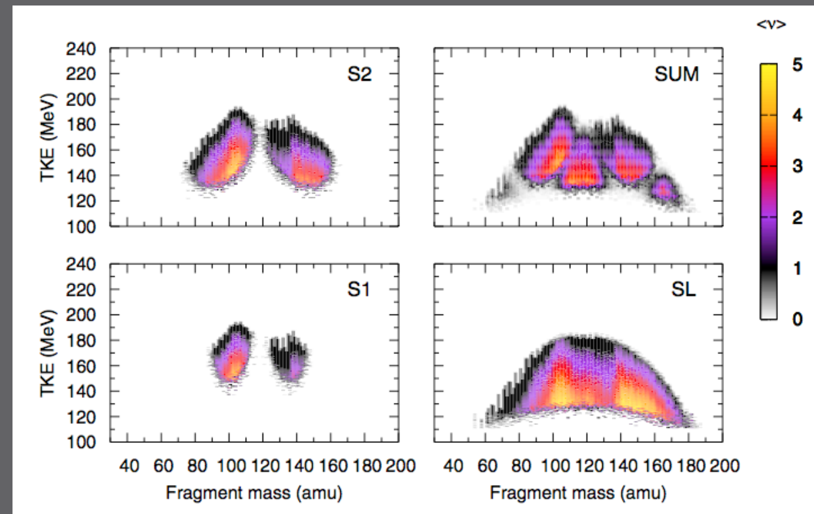

Fig. 2. Average prompt neutron multiplicity <ν>(Fragment mass,TKE) for each fission mode.

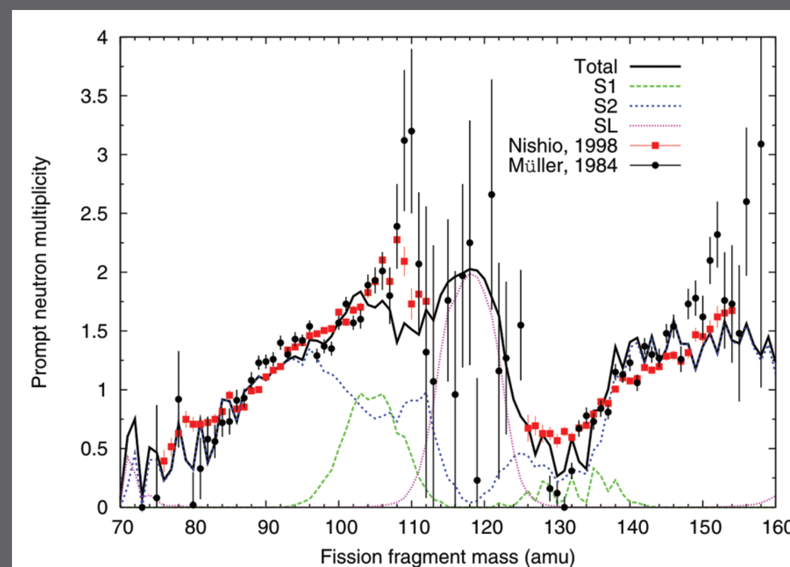

Fig. 3. Projection of results shown in Fig. 2 on the fission fragment mass axis and compared with existing experimental data.